1668年郯城地震断层的长发震间隔与低速率证据

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摘要 郯庐断裂是我国东部规模最大的发震断层, 曾发生过公元前70年安丘7级地震和1668年郯城8½级大地震, 其地震危险性一直备受关注。然而因郯城地震断层的古地震历史及滑动速率的定量研究不足, 制约着区域地震危险性评价工作。因此, 本研究通过卫星影像及早期航片解译和郯城东北华桥一带的古地震探槽揭露, 并利用AMS-¹⁴C测年方法, 定量限定郯城地震断层中段的最新一次古地震事件年龄为距今约12.8±4.0/-3.7 ka之前, 指示该段断裂在最近一次地震旋回中的大震复发间隔长达一万年以上。同时, 结合郯城地震断层约9 m的特征滑动量, 估计其晚更新世末以来的右旋走滑速率约为0.7 mm/a, 显示为低滑动速率特征, 符合区域大地测量观测结果所反映的华北地区整体为低应变速率环境的认识。根据新的研究结果推断, 低的断裂滑动速率和长达万年尺度的大震复发间隔可能是郯庐断裂晚第四纪活动的主要特征, 这将为科学评价郯庐断裂的潜在地震危险性提供重要地质约束。

关键词 郯庐断裂, 1668年郯城地震, 古地震, 复发间隔, 滑动速率

活动断裂的滑动速率与大震的复发间隔是活动构造定量研究与地震危险性评价的重要参数^[1]。郯庐断裂处于我国东部人口密集和经济发达的地区, 曾发生公元前70年安丘7级地震和1668年郯城8½级大地震, 因此, 其地震危险性一直备受关注, 其全新世活动性与古地震问题也一直是地震地质领域关注的重点。近年来, 沿郯庐断裂带的不同段落也取得了许多新的研究成果, 包括: 依兰-依通段全新世破裂的发现^[2,3]及古地震历史^[4,5]、江苏段的古地震历史^[6-10]、以及安徽段全新世活动断裂的发现^[11-14]等。同时也提出了如何更科学地评价郯庐断裂带所穿越的我国东部地区的潜在地震危险性问题。而定量约束郯城地震断层的古地震复发间隔及滑动速率显然是正确认识郯庐断裂潜在发震能力及风险的关键所在。

然而, 该段仅有的古地震研究结果^[15]获得的大震复发间隔(3.5 ka)明显小于其他段落^[4-14,16]。究其原因, 可能由于通过多个不同探槽剖面约束不同的古地震事件, 并且没有单个探槽完整记录古地震事件序列, 因此结果可能存在很大的不确定性^[17-19]。另一方面, 华北地区GPS观测结果显示, 跨郯庐断裂带各个段落两侧的速度没有明显的差异^[20-22], 而对该段的滑动速率估值(2~3 mm/a)^[23,24]也较高, 且明显高于其他段落的研究结果^[4,25]。因此, 非常有必要对该段的古地震及滑动速率开展进一步的研究。

本文通过对1668年郯城地震断层开展古地震探槽研究, 揭示了最新一次古地震事件的发生时间及大地震复发间隔, 并估计了郯庐断裂的滑动速率, 从而为该区的地震危险性评价提供了新的地质约束。

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1 地质背景

郯庐断裂是我国东部规模最大的断裂,南起长江北岸的广济地区,向北经安徽、江苏、山东,跨越渤海,经东北三省,进入俄罗斯境内,在我国境内长达2400多千米,总体走向NNE^[26-28](图1)。其早期经历了大规模的左行滑移^[26],晚白垩世至早第三纪期间发生强烈伸展变形,形成“两堑夹一垒”构造^[28]。晚第四纪以来的断层性质以右旋走滑为主兼有逆冲分量,并且断裂活动主要集中在东侧地堑内新发育的F5断裂上^[6,32-34],也是郯庐断裂带中的主要发震断层。

郯庐断裂带活动断层在渤海湾以南,北起潍坊,过临沂,经宿迁,可到安徽境内,全长约500 km;自北向南可划分为3段:安丘段、莒县-郯城段、新沂-泗洪段^[35]。沿其中的安丘段和莒县-郯城段曾分别发生过公元前70年安丘7级地震和1668年郯城8½级地震(图1)。但因历史记载不详,对于1668年郯城地震的地表破裂范围至今存在异议,主要有4种观点:(1)北起莒县,经临沂至江苏宿迁,长约230 km^[8,36,37];(2)从莒南左山至新沂何庄,长约120 km,或至宿迁北长约160 km^[6,38];(3)从莒县小土岭至郯城窑上,长约130 km^[32,39,40];(4)从莒县土岭至新沂何庄,长约150 km^[41]。

本研究开挖探槽的位置处于上述观点都认可的1668年郯城地震地表破裂的郯城东北部的华桥段(图2)。该段在航片上的断层迹线清晰,可见一系列冲沟沿断层被明显右旋位错的现象,而且断层两侧的冲沟密度也出现了明显不同(图2)。

2 探槽揭露的最新古地震事件

由于我国东部地区人为改造严重,仅通过最新的地貌影像对断裂的展布位置很难约束。本文利用早期航片与最新影像进行对比分析,并选取人为改造较少的区域,结合野外考察,发现了1668年地震所形成的1条地表连续性较好,长约80 m、高约2.5 m的断层陡坎(图3),陡坎两侧的1条冲沟被右旋位错约36 m。受开挖许可环境所限,本文仅在陡坎的两边各开挖了1个探槽。

探槽1总长9 m,深2 m(34°49′23.02″N/118°29′38.94″E),揭露了5个地层单元(图4),从老到新分别为:U1上白垩统王氏组二段砂岩,颜色以紫红色和浅绿色为主;U2姜黄色黏土层夹有少量岩石碎块、砂砾,根据区域第四纪地层时代分析其为晚更新世地层;U3断层变形带,紫红色黄绿色砂泥岩,沿断层面发育几厘米

厚的断层泥;U4浅黄色黏土夹有碎石块,为残坡积物,推测为全新世地层;U5耕作土。沿探槽两壁可发现两组断裂:F1断裂倾向西,倾角56°~68°;F2由2~3支次级断裂组成,倾向东,倾角28°~64°。U2沿两条断层逆冲到U4之上,在剖面上显示为典型的正花状构造,并在地貌上形成陡坎,反映了郯庐断裂莒县-郯城段以走滑为主兼有逆冲的运动学性质,这与郯庐断裂活动时的应力状态^[32-34]及现今我国东部地区NEE向的最大主压应力方向都是一致的^[42,43]。

探槽2总长13 m,深3 m(34°49′25.98″N/118°29′39.34″E),揭露了6个地层单元(图5),从老到新分别为:U1白垩纪砂泥岩风化产物;U2断层泥,厚达十几厘米;U3浅紫红色黏土、浅黄绿色砾石团块、姜黄色黏土混杂堆积物,应为大地震后快速崩塌堆积产物;U4紫红色砂砾石层,具有明显的层理,为流水作用形成,在本层底部采集的碳屑样品的AMS-¹⁴C测年结果分别为9255~9030, 16856~16351和12883~12703 a BP(所有样品由Beta实验室通过AMS方法测年,2σ(置信度95.4%)的校正年龄,下同);U5紫红色砂砾石层,为残坡积物,无层理,样品测年结果为8360~8186 a BP;U6姜黄色黏土层,为坡积物,样品测年结果为152~56 a BP,该层被1668年郯城地震错断,沉积年龄应老于1668年,因此所测样品可能为后期植物根茎。综合探槽2剖面中地层单元的沉积特征与成因推断,其中层U3应为最新一次古地震后快速崩塌堆积的产物,之后在震间应断坎坡度变缓形成层理发育的层U4堆积,可对应断层崩积楔上部粒度相对较细的冲刷相沉积,因此最新古地震的年龄应该发生在层U4底部沉积之前,但可能比较接近其底部年龄。利用Zecher和Frankel^[44]的Matlab码生成的U4底部3个样品的平均年龄为12.8±4.0/-3.7 ka。因此可以确定,郯城地震断层中段的最新一次古地震发生在距今约12.8±4.0/-3.7 ka之前。之后,1668年郯城地震又断错到地表,致使东侧的晚第四纪地层逆冲到基岩风化物之上,形成了高约2.5 m的地表断坎。

3 讨论

3.1 郯庐断裂带的古地震历史及大震复发间隔

林伟凡等人^[15]早期通过多个探槽开挖对莒县-郯城段的古地震进行了初步限定,认为有3次古地震事件,其年代大约距今3500, 6000~7000, 10000 a;最新事件的年龄下限源于左山剖面断错了4160±95 a的地层,上限

图 1 郯庐断裂活动断层及邻区构造地貌图; 左上角郯庐断裂带分布图引自Zhu等人^[29], 断层展布数据引自徐锡伟等人^[30], GPS数据来自中国地震局地质研究所王敏研究员; 小震精定位结果来自朱艾斓等人^[31]

Figure 1 The tectonic setting and geomorphology of the Anqiu-Juxian fault of the Tanlu fault zone and adjacent regions. The distribution map of Tanlu fault zone in the upper left corner after Zhu et al.^[29]. The faults from Xu et al.^[30]. The grey arrows are horizontal-component GPS velocity field from Wang Min, a researcher at the Institute of Geology, CEA. The relocated microseismicity from Zhu et al.^[31]

源于断面上沉积了 3170 ± 80 a的坡积物; 第2次事件是钟华山剖面基岩断层上覆 7105 ± 95 a地层有扰动变形和液

化痕迹, 另一剖面基岩断层坎被 5710 ± 90 a的地层覆盖; 第3次事件通过地层对比推测的年龄。其研究结果通过

图2 郯庐断裂华桥段1964年航片(a)及断层解译图(b)

Figure 2 Aerial photograph captured in 1964 along the Huaqiao segment of the Tanlu fault (a) and its interpretation (b)

图3 探槽位置的1964年航片(a)、2015年Google Earth影像与断层陡坎(b)及探槽开挖环境照片(c,d)

Figure 3 The trenches site of aerial photograph captured in 1964 (a), Google Earth image of the same area in 2015 (b) and field photos (c,d) show the fault scarps and the situation around the trenching sites

图4 探槽I两壁剖面图

Figure 4 The log of two walls of the trench 1

多个不同探槽剖面约束不同的古地震事件, 存在很大的不确定性。本研究基于郯城地震断层中段的探槽剖面揭示了1668年郯城历史地震和在U4地层沉积之前发生的最近一次古地震事件, 并基于U4底部的3个AMS- ^{14}C 测年结果定量限定了该次古地震的上限年龄。虽然因3个年龄结果相差几千年, 很难精确限定古地震发生的具体时间, 但取其平均年龄 $12.8 \pm 4.0 / -3.7 \text{ ka}$ 可近似代表古地震发生的最晚时间。这表明郯城地震断层在最近两次大震的时间间隔超过了1万年, 显示出长复发间隔特征。

Min等人^[3]在依兰-依通段方正县发现存在全新世晚期活动的证据, 断错 1730 a BP的地层; 舒兰县最新一次活动被约束在4410~2510 a BP之间。疏鹏^[4]把方正县最新断错约束在1730~684 a BP之间, 倒数第二次事件发生在28.5~21.7 ka之间, 第三次地震事件发生在35812 a~33.0 ka之间。Yu等人^[5]在多处开挖了探槽, 约束该断裂多段丛集破裂发生在3个时期大约34750~35812, 21700~22640和4000 a BP至今。可以初步确定依兰-依通段在距今三万多年以来发生过3次古地震。

杨晓平等人^[16]在安丘段青峰岭的探槽揭示了最新一次古地震事件的发生年代距今约1.07万年, 同时认为可能存在距今2.18万年的古地震事件。该段距今两万多年以来发生过2次古地震。

李家灵等人^[45]在江苏段何庄T1阶地测得 ^{14}C 年龄为 $3510 \pm 165 \text{ a}$, 根据李起彤^[46]在重岗山测得断错地层年龄为 $4960 \pm 135 \text{ a}$, 认为最新活动年代为3510~4960 a; 在宿迁嶂山, 根据彭贵和焦文强^[47]在裂缝中充填物的测

年结果分析第二次古地震在8230~5250 a, 接近8230 a; 这些证据可能只揭示了全新世晚期的一次事件, 因此该结果存在很大疑问。曹筠等人^[9]在重岗山的探槽显示断层错断 $2.5 \pm 0.1 \text{ ka}$ 地层。沈小七等人^[7]在重岗山通过3个探槽揭示了2次古地震事件, 其年代依次为 $11755 \pm 45 \sim 10525 \pm 45 \text{ a BP}$ 与 $10135 \pm 50 \sim 8155 \pm 45 \text{ a BP}$, 但这个结果是值得商榷的, 因为如果其探槽中 $10525 \pm 45 \text{ a BP}$ 样品是二次沉积, 这两次事件可能是一次事件; 同时其TC6中断层上延虚线存在切穿 $8155 \pm 45 \text{ a BP}$ 样品沉积地层的可能, 如此其结果只揭示了 $8155 \pm 45 \text{ a BP}$ 以来的一次事件, 与曹筠等人^[9]的结果一致。另外, 曹筠^[8]通过对何庄、新沂河北及合欢路3个探槽约束了5次古地震事件的时代, 分别为3.8 ka以来, 6.2~13.4, 33.9~45.3, 46.2~50.4和66.5~83.9 ka。赵鹏等人^[12]在大红山的探槽约束了最近古地震事件发生在12~2.5 ka。因此, 江苏宿迁距今四万多年以来发生过4次古地震; 重岗山、大红山和浮山段, 全新世期间最多发生过一次古地震。

赵朋等人^[13]在安徽浮山的探槽显示最新古地震事件发生在距今 $10.6 \pm 0.8 \sim 7.6 \pm 0.5 \text{ ka}$ 。杨源源等人^[14]在紫阳山的探槽显示倒数第2次古地震事件发生在距今20.10~13.46 ka, 最新古地震事件年代为距今约10.9 ka以来。而安徽段距今约两万年以来发生过2次古地震。

通过总结分析郯庐断裂带上已有的古地震数据(图6), 如果排除存在疑问的事件, 综合上述各个段落的地震研究结果可知, 整个郯庐断裂带上晚更新世晚期以来的大震复发间隔平均都在万年左右, 这与本文对

图5 探槽2两壁剖面的正射影像与解译图

Figure 5 Orthophoto map and the interpreted map of the both wall of the trench 2

郯城地震断层中段的研究结果近似, 也显示出长复发间隔的特征。

3.2 郯城地震断层的滑动速率

前人曾利用多种方法对郯庐断裂带不同段落的右旋走滑速率进行过研究. Huang^[23]假设冲沟偏转角与断层时间呈线性关系, 估计了郯城地震断层的大地震发生间隔是4 ka, 结合位错量8 m, 估算了滑动速率为2 mm/a; Jiao等人^[24]假设裂点的后退速率与时间呈线

性关系, 计算出最新裂点的后退速率, 反推出早期裂点的形成时间, 结合冲沟走滑位错量, 估算了郯城地震断层的滑动速率约为2.86 mm/a; 通过地貌演化与断层位错的关系, 推测滑动速率有很多的假设, 其结果存在很大的不确定性. 疏鹏^[4]通过对依兰-依通段上冲沟位错的分析及光释光测年, 限定该段断裂晚更新世晚期以来的右旋滑动速率为0.41~0.7 mm/a; 宋方敏等人^[25]在安丘段, 利用热释光测年方法确定断错冲沟约64~73 m的位移发生在约69.64 ka以来, 限定该段断裂的右旋走

图6 郯庐断裂活动断层古地震研究成果图

Figure 6 Paleoseismic study along the active fault of the Tanlu fault

滑速率为0.91~1.04 mm/a. Zhang等人^[22]通过提取跨郯庐断裂两侧平行与垂直断裂走向的GPS速率剖面, 显示断裂两侧没有明显的差异运动; 王敏等利用GPS观测结果计算的速度场数据同样显示断裂两侧GPS速度没有明显变化(图1), 这都指示了跨郯庐断裂的现今应变累积速率较低.

李家灵等人^[35]通过野外考察实测的郯城地震断层的最大水平位移在7~9 m; Jiang等人^[36]通过早期影像分析了郯城地震断层的累计位错分布, 获取了郯城地震同震平均位错9 m, 并且发现4次古地震的累计位移恰好是郯城地震同震位移的整数倍, 认为郯城地震断层破裂行为服从特征滑移模型. 尽管目前有限的古地震资料还不能确定郯城地震断层的大地震复发一定符合准周期地震模型, 但是基于本研究获得的大地震发生间

隔, 可以初步限定郯城地震断层的应变累积速率大约为 $0.7+0.11/-0.16 \text{ mm a}^{-1}$, 这一结果与前人在郯庐断裂带的依兰-依通及安丘段的估算结果非常接近, 也符合华北地区现今主要处于低应变速率场环境下的认识^[20]. 考虑到震间断层的应变累积速率可以近似作为断裂滑动速率的替代指标^[48,49], 因此, 笔者认为郯城地震断层的晚更新世末以来的右旋走滑速率约为0.7 mm/a.

4 结论

通过探槽揭示了郯城地震断层呈现典型的正花状构造样式, 结合断错地貌, 指示了郯庐断裂的运动学性质以右旋走滑为主兼有逆冲分量, 符合区域应力场结果. 通过碳十四测年, 约束了最新一次古地震事件年龄接近 $12.8+4.0/-3.7 \text{ ka}$, 郯城地震断层的大震复发间隔

在万年左右,与其他段落的结果基本一致.结合1668年郯城地震断层约9 m的特征滑移量,估计了该段晚更新世末以来的右旋走滑速率为0.7 mm/a,并与大地测量学获得的华北地区处于低应变速率场一致.因此,我们认

为低的断裂滑动速率和长达万年尺度的大震复发间隔是郯庐断裂晚第四纪活动的主要特征.这一新的研究结果可为科学评价和理解郯庐断裂的潜在地震危险性提供重要的地质约束.

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Summary for “1668年郯城地震断层的长发震间隔与低速率证据”

Evidence of long recurrence times and low slip rate along the 1668 Tancheng earthquake fault

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Fault slip rates and recurrence intervals of large earthquakes for active faults are important parameters for better understanding active faults and assessing their seismic hazard. The Tanlu fault, located in the densely populated and economically developed area of eastern China is thought to be the source of the M 7 Anqiu earthquake in 70 BC, and M 8½ Tancheng earthquake in 1668. Understanding the recurrence interval of paleoearthquakes and fault slip rates for the Tancheng earthquake fault is critical for assessing the potential for seismic risk and assessment for the Tanlu fault. However, the only published study used several trenches and a single trench does not completely record the sequence of paleoearthquake events, leaving a large uncertainty of seismic hazard. GPS observations in North China show that there is no significant velocity gradient across the Tanlu fault, yet the long-term slip rate of the Tancheng segment of the fault is estimated to be significantly higher, up to 2 mm/a. Therefore, it is critical to conduct further research on the paleoearthquake history and slip rates of this fault segment to reconcile these contrasting results.

In this study, we utilize aerial photographs and high-resolution satellite imagery, combined with field investigations of a surface rupture formed by the 1668 earthquake. The earthquake rupture is ~80 m long and ~2.5 m high, located in the Huaqiao village of northeastern Tancheng County. A gully across the rupture reveals a right lateral dislocation of approximately 36 m. We excavated two trenches on both sides of the rupture. Trench 1 reveals a positive flower structure and is consistent with a right lateral strike-slip fault with a thrust component consistent with the modern regional stress field. Trench 2 reveals a colluvial wedge formed by the latest paleoearthquake with a fine-grained deposit overlapping the colluvial wedge. The latest paleoearthquake should occur prior to deposition of the fine-grained deposit. AMS-¹⁴C radiocarbon dating was used to determine the age of the event and is approximately 12.8±4.0/–3.7 ka, indicating a recurrence interval of large earthquakes greater than 10 ka, consistent with the results from other segments of the Tanlu fault. Combined with an average slip of ~9 m for the 1668 Tancheng earthquake, the dextral slip rate along the Tancheng earthquake fault since the end of the late Pleistocene is estimated to be 0.7 mm/a, consistent with low interseismic strain accumulation based on geodetic observations across the North China region.

Tanlu fault, 1668 Tancheng earthquake, paleoearthquake, recurrence times, slip rate

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